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Rising Sea Levels

Sea level rise increases the frequency and severity of coastal flooding and rates of coastal erosion. Sea level rise will continue far beyond the 21st century, even if global temperature increase is limited to 2°C above pre-industrial levels. This POSTnote sets out the causes and likely future levels of sea level rise and its implications. It updates POSTnote 363 on Sea Level Rise, published in September 2010.

Overview

- Global average sea level has risen by 20 cm over the last century. It will continue to rise, but how much and how fast it rises depends on human greenhouse gas emission levels.
- Sea level change varies locally from the global average. Local sea level rise will be higher in southern England than in Scotland.
- Sea level rise increases the risk of coastal flooding and erosion. 50 cm of local sea level rise would make about 200 km of UK coastal flood defences vulnerable to failure.
- The impacts of coastal flooding are highest during extreme sea level events, which will become more frequent as sea levels rise.
- Shoreline Management Plans provide the framework for coastal adaptation planning.

Background

Global mean sea level (GMSL) has risen 20 cm since 1900, at an average rate of 1.5 mm per year during 1901-1990.[1,2] During 1993-2014 it rose on average 3.2 mm per year.[3] The rate of sea level rise during the 20th century was faster than at any point since reaching near modern-day levels around 3,000 years ago.[4] Higher sea levels increase the likelihood of coastal flooding and speed up coastal erosion, which poses problems for UK coastal communities, businesses, infrastructure and habitats.[5] Current UK annual damages from coastal flooding are estimated at £540 million per year, and will almost certainly increase with future sea level rise.[6]

Causes of Sea Level Rise

Human greenhouse gas (GHG) emissions have increased global surface temperatures,[7] which causes sea level rise in two main ways:[8]

- **Thermal expansion.** The oceans increase in volume as they become warmer.
- **Added water.** The amount of water in the oceans is increasing as ice sheets and glaciers melt.

From 1993 to 2014 GMSL rose 6.4 cm. 40% of this rise was caused by thermal expansion, 20% by the Greenland and Antarctic ice sheets and 25% by glaciers elsewhere. The final 15% was due to other forms of water transfer from land into the ocean, such as human groundwater use.[3]

Ice Sheet Contribution to Sea Level Rise

Satellite observations show that the net sea level contributions from the Greenland and Antarctic ice sheets increased considerably over the past decade.[9,10] During 2005-2014 they contributed 21% and 11% respectively, accounting for almost a third of total GMSL rise.[3,11] Their contributions are projected to continue to increase because of climate change, but the future rate is uncertain.[8]

The Greenland and Antarctic ice sheets, which hold by far the largest potential future sea level contributions, cause sea level rise through two primary processes of ice loss:

- **Surface Melting.** The ice sheet volume decreases when surface melting in summer (ablation) exceeds accumulation from snowfall. If the meltwater runs off into the ocean, it contributes to sea level rise.
- **Ice Sheet Dynamics.** Acceleration of ice sheet flow increases iceberg calving and ice loss into the ocean.

Greenland Ice Sheet

Summer temperatures in Greenland are high enough for the ice sheet to experience widespread surface melting, which is projected to be the dominant process of future ice loss.[12] There is evidence that a sustained temperature increase above a certain threshold (between 1.6°C-4°C above pre-industrial levels[13,14]) will cause near-complete loss of the ice sheet, with GMSL rise up to 7 m in over a millennium.[8]

Antarctic Ice Sheet
In contrast to Greenland, the current climate in Antarctica is so cold that most of the ice sheet is not affected by surface melting; ice loss is mainly due to ice sheet dynamics. The Antarctic ice 'sheet' rests on bedrock and extends out over the surrounding ocean as floating ice 'shelves'. These ice shelves have a buttressing effect, slowing the flow of the ice sheet into the ocean. Thinning or breakup of ice shelves, caused by atmospheric warming from above and oceanic warming from below, reduces their buttressing effect and leads to accelerated ice sheet flow towards the ocean.[15] Observations show that, on average over 1994-2012, Antarctic ice shelves thinned at accelerating rates. Minor thickening of some ice shelves in East Antarctica was more than offset by rapid thinning of West Antarctic ice shelves.[16]

The 'grounding line' is the boundary between the floating ice shelf and the ice sheet grounded on the bedrock. As the ice shelf thins and oceanic warming melts the ice at the grounding line, previously grounded ice becomes afloat. In areas where the bedrock behind the grounding line is below sea level and slopes downward, such as West Antarctica, the grounding line retreats deeper and further under the ice sheet. As ice sheet flow speed is proportional to ice sheet thickness at the grounding line, this retreat leads to further ice shelf thinning and grounding line retreat. This process, called 'Marine Ice Sheet Instability' (MISI), is self-sustaining until the grounding line reaches a point where the bedrock rises upward again.[17] In West Antarctica, where the ice sheet rests on a bedrock basin that extends well below sea level, MISI could eventually cause much of the ice sheet to become afloat and collapse.[18] Most of the East Antarctic ice sheet is grounded above sea level, but some parts that are grounded below sea level may also be vulnerable to MISI.[19]

Past and Future Sea Level Change
Changes in sea level occur on a range of timescales, from hours (e.g. tides) through to centuries and millennia. It is impossible to predict future sea level rise exactly, but computer models can provide projections of the range of possible future changes. These projections depend on future GHG emissions and subsequent rates of temperature increase, as well as model uncertainties. See POSTbrief 25 on Projecting Future Sea Level Rise for more details.

21st Century Changes in Sea Level
In 2013, The Intergovernmental Panel on Climate Change (IPCC) projected a 66% or greater likelihood that GMSL rise by 2100 will lie within the ranges of 28-61 cm, 36-71 cm or 52-98 cm for a low, medium or high GHG concentration scenario respectively. The IPCC states that additional GMSL rise above these ranges could be caused by a collapse of marine-based sectors of the Antarctic ice sheet initiated through MISI.[8] Several studies since the IPCC report have suggested that MISI may already be underway in West Antarctica.[20,21,22] Quantifying this potential additional Antarctic contribution currently presents the largest source of uncertainty in future sea level projections (POSTbrief 25).

Local Variations in Sea Level Change
Sea level change is not uniform globally. Tide gauge observations show that sea level around the UK has risen on average 1.4 mm per year since 1900, slightly below the global average.[23,24] Sea level change varies locally from the global average due to a range of factors, including:

- **Gravitational effects**. The mass of the present-day ice sheets pulls ocean water towards them and distorts sea level globally. Ice sheet mass loss causes sea level to drop locally and rise further afield; for instance, ice loss from Greenland causes sea level rise above the global average in the tropics, and below average in Europe.[25]
- **Changes in ocean circulation patterns**. For example, studies suggest that changes in the Atlantic overturning circulation and the Gulf Stream could cause higher sea level rise along the US east coast than in Europe.[26,27]
- **Vertical land movement**. Relative sea level (RSL), defined as the sea level relative to the Earth's crust, takes into account the movement of the land as well as the sea. Much of the land in Northern Europe is still readjusting after it was weighed down by large ice sheets during the last Ice Age. For example, southern England is subsiding by about 1-2 mm per year, whereas Scotland is rising by a similar amount.[28] This means RSL rise is higher in London than in Edinburgh.

Relative Sea Level Projections for the UK
RSL is the preferred metric to inform local impact and adaptation planning. The most recent projections of future UK RSL were published as part of the Met Office UK Climate Projections (UKCP) in 2009,[29] before the latest IPCC projections.[8] The Met Office is currently advising users to wait for the new UKCP, due to be published in 2018. Preliminary work suggests the new RSL projections will be 20-30% higher than those from 2009.[30] In 2009, the UKCP included a worst case scenario of 1.9 m of RSL rise by 2100 (named 'High++'), intended for adaptation planning where high levels of protection are required,[29] such as in the Thames Estuary (Box 1). The new UKCP will report on an updated 'High++' scenario for 21st Century sea level rise. It will also report on related work for the Environment Agency (EA) to provide RSL projections beyond 2100.

Changes in Sea Level over Millennia
During the Last Glacial Maximum (20,000 years ago), when the ice sheets were much larger, GMSL was approximately 130 m lower than today. Subsequent warming of about 4°C caused those ice sheets to shrink and sea level to rise to near modern-day levels. However, while temperatures stabilised roughly 11,000 years ago, the ice sheets took a further 8,000 years to stabilise, so sea level continued to rise by a further 45 m before reaching near-modern levels around 3,000 years ago.[31] Geological records show that during slightly warmer periods in the past, when the ice sheets were smaller than today, GMSL has exceeded 5 m above present-day levels.[8] For example, during the Last Interglacial (129-116,000 years ago), when global temperatures were similar to today, GMSL was 6-9 m higher than at present.[32]

Beyond 2100: Long-term Sea Level Rise Commitment
The 2015 Paris Agreement aims to cut GHG emissions to keep global temperature increase "well below" 2°C above pre-industrial levels, and "pursue efforts" to limit it to 1.5°C.[33] However, even if these targets are met, sea level rise will continue throughout the 21st century and for many centuries beyond because GHGs remain in the atmosphere for a long time and there is significant inertia of the climate system.[31] Nonetheless, the amount and rate of short- and long-term sea level rise will depend on emission levels in coming decades. Unabated emissions would further accelerate the rate of sea level rise and lock in ice sheet contributions of many metres, over centuries to millennia.[34,35,36]

Implications of Sea Level Rise for the UK
Local sea levels are highest during extreme events, which can lead to coastal flooding and erosion. Extreme sea level events arise from a combination of waves, tides and storm surges. When the atmospheric pressure on the sea surface is reduced during storms, the sea level temporarily rises. Combined with strong onshore winds, this causes storm surges, such as during the 2013/14 UK winter storms which caused widespread coastal flooding.[37] Sea level rise makes extreme sea level events more frequent for two reasons: it reduces the level of beaches through increased erosion and because the sea level is higher, the added height from extreme sea levels required to cause coastal flooding is less.[38] For example, in the Thames Estuary (Box 1), a current 0.1% annual chance of coastal flooding increases to a 0.7% annual chance with 50 cm of sea level rise, and becomes an 8.3% annual chance with 1 m of sea level rise.[12] Climate change can, in principle, also affect extreme sea level events by increasing storminess,[44] which some have argued may have been a factor in the 2013/14 storms.[45] However, it is mean sea level rise that has been shown to be the dominant contributor to the rising trend of extreme sea level events,[46] and is likely to continue to be so.[29] Exposure to coastal flooding is also increased by growing population, property assets and infrastructure in coastal areas.[47,48]

In the UK Climate Change Risk Assessment 2017 (CCRA), the Committee on Climate Change (CCC) identifies flooding and coastal change as one of six top climate change risks to UK communities, businesses and infrastructure.[5] Coastal flooding is also a top four priority risk in the National Risk Register.[49] If current defences are maintained, around 2,000 properties are at risk of being lost to coastal erosion in the next 50 years.[50] Coastal erosion rates will increase with sea level rise.[51,52] Modelling work undertaken for the CCRA analysed the future risk of coastal flooding for the UK and concluded that 50 cm of RSL rise would make 200 km of coastal flood defences (20% of total length of defences in England) highly vulnerable to failure. If these defences were lost, the number of properties estimated to be exposed to an extreme sea level event with a 0.5% annual chance of occurring would increase from 122,000 to 312,000.[53]

Box 1. Case Study: Thames Estuary 2100 Plan (TE2100)
There are 1.3 million residents and an estimated £275 billion of property assets located in London and the Thames Estuary floodplain. The TE2100 Plan sets out the Environment Agency's strategy to protect this area from coastal flooding up to 2100 and beyond,[39] and was approved by Defra in 2012. It covers an extensive system of coastal defences, including the Thames Barrier, other smaller barriers, 350 km of flood walls and embankments, pumping stations and flood gates. The plan uses an 'Adaptive Pathways' approach, using a baseline estimate of 90 cm of RSL rise by 2100, which is adaptable to changes in the rate of RSL rise up to a worst case scenario of 2.7 m by 2100, based on the UKCP 'High++' scenario. To this end, the plan identifies 10 indicators of change that will trigger certain adaptive responses or major interventions (e.g. a new Thames Barrier) at an earlier or later time, as required.

Relative sea level rise is one such indicator, and local monitoring shows that RSL in the Thames Estuary rose at a rate of 4.5-4.7 mm per year during 1999-2014, higher than both the global average and the projected rate of 4 mm per year in the TE2100 plan.[40] However, the average for the past 70 years is still below both of these. Lead-in times are crucial, as sufficient warning of accelerations in RSL rise is required to start planning for major interventions. As part of a NERC grant, TE2100 is working together with researchers to reduce these lead-in times and detect accelerations sooner.[41] With 50 cm of RSL rise, a new Thames Barrier will need to be built further downstream. This is projected to happen in 2070, but could be as soon as 2055 with higher rates of RSL rise, and decision-making and planning will need to start at least 20 years prior. Beyond 2100, London could be protected with defences against long-term sea level rise of up to 5 m.[42] Protection against higher levels of sea level rise would involve high-volume mechanical pumping to drain the River Thames.[43]

Coastal Adaptation and Management
Sea level rise, both in the short and long term, presents one of the biggest adaptation challenges to climate change.[47,54] The UK CCRA recommends that more action is needed to reduce risks from coastal flooding and erosion to infrastructure services (Box 2), and to coastal habitats and heritage with the potential loss of natural flood protection.[5]

Infrastructure Resilience
Much critical UK infrastructure is located along the coast, including roads, railways (Box 2), ports,[55] and nuclear power stations,[56] which need to be resilient to coastal flooding and erosion, and long-term future sea level rise. Critical national

Box 2. Case Study: Railway Line at Dawlish, Devon
The coastal railway line at Dawlish is the only rail link to South Devon and Cornwall and one of the most expensive sections of the network to maintain, at an estimated £2.1 million per year.[6] During the winter storms of 2013/14, part of the sea wall at Dawlish was breached and a section of the railway washed away, severing rail links to the South West for two months as repairs were carried out, with direct costs estimated at £50 million. Line restrictions and closures due to coastal flooding are projected to increase from 10 days per year to 30-40 days per year by 2040 and up to 84-120 days per year by 2100, for a RSL rise scenario of 55-81 cm, with associated increased maintenance costs of £5.8-£7.6 million per year.[57] A recent Network Rail resilience study concluded that maintaining the line in its current position and strengthening the sea walls (estimated cost of £398-£659 million over 20 years) is better value for money than re-opening an old unused line north of Dartmoor (at a cost of £875 million), or building a brand new line between Exeter and Newton Abbot (up to £3.1 billion).[58]

Box 3. Managed Realignment
Managed realignment is the strategic relocation of structures or change in land use to manage coastal flood and erosion risk and limit environmental damage. It can provide a useful alternative adaptation option to holding the line, and may be more cost effective in certain situations.[59] It can also reduce pressures on coastal defences, and create new habitats that can act as natural flood protection.[60] Many Shoreline Management Plans recommend holding the line in the short term up to 2025, but switch to managed realignment thereafter, with about 10% of the coast of England and Wales likely to see realignment by 2030, and almost 15% by 2060. Achieving this will require an increase in the current rate of managed realignment, from 6 km to 30 km per year.[61] Implementation of managed realignment can face political, social and funding challenges,[59] although community support increases if flood risk is reduced, e.g. at Steart in Somerset and Medmerry in Sussex.[62,63]

infrastructure is organised into 13 sectors, such as energy and transport. Each has a lead Government Department responsible for assessing the sector's resilience and working to improve it if necessary, in annually produced Sector Resilience Plans.[64]

Shoreline Management Plans
Because of the length and varied nature of the UK coastline, no single coastal adaptation approach is suitable for all regions. Non-statutory Shoreline Management Plans (SMPs) set out locally-specific long-term coastal management strategies.[65] SMPs recommend approaches to managing the flood and erosion risks to the coastline in the short term (up to 2025), mid-term (2025-2055) and long-term (2055-2105). In England and Wales, 22 SMPs have been developed by Coastal Groups, with members from local councils, the EA or Natural Resources Wales (NRW), to cover the entire coastline. Scotland faces less pressure from coastal flooding, because of upward land movement, lower population density and smaller flood plains. The Scottish Environment Protection Agency (SEPA) and local authorities have developed SMPs for eight sections of Scottish coastline that are vulnerable to coastal flooding and erosion.[66,67] Northern Ireland currently has no SMPs, but their development is being considered.[68]

SMPs were first developed in the mid-1990s, and updated to a second round, SMP2, in 2006-2012, which factor in sea level rise projections. SMP2 recommendations are informed by natural coastal processes, but are also influenced by an understanding of the value of the assets at risk versus the potential cost of maintaining, or building, coastal defences to keep the coastline in its current position. SMPs recommend four different coastal management policy options:[69]

- **Hold the line.** Defend coastline position with hard (e.g. sea walls) or soft (e.g. beach nourishment) defences.
- **Advance the line.** Build new defences on seaward side to reclaim land. Rarely implemented in the UK.
- **Managed realignment.** Allow coastline to retreat to a new line of defences further inland (Box 3).
- **No active intervention.** Let coastline evolve naturally.

Implementation of SMPs is managed by the Coastal Groups, with local authorities managing coastal erosion.

Box 4. Case Study: Fairbourne, Wales
Fairbourne is a coastal community in Gwynedd, North Wales, built behind a shingle bank on a low coastal plain, with about 500 properties and 1,100 residents. The village is currently just above the mean high water mark, but without further protective action it will face regular inundation with sea level rise of 36 cm or more. Depending on the rate of sea level rise, this could happen as soon as the 2050s. With 50 cm of sea level rise, perhaps by around 2070, the village will become unsustainable in its current location.[61] The SMP for Fairbourne recommends managed realignment for some areas around the village as soon as 2025, and for the village itself from 2055. It states that the village's coastal defences can and should be maintained for the next 40 years (from 2014), but beyond that time the community should be relocated to avoid catastrophic flood risk.[70]

Fairbourne is the first UK case of having to move a community because of sea level rise, and therefore raises new challenges. When the SMP was adopted by Gwynedd Council in 2013, there was a lack of clarity in communicating the risks and the SMP timeline to residents and the media, leading to some reports claiming the village would be lost as soon as 2025, instead of 2055. Property values in the village were affected, which may have further financial implications for residents.[71] It is also unclear where the residents should be relocated to, and how the move will affect local businesses. A community action group, Fairbourne Facing Change, was set up in 2014 to challenge the SMP. In response, Gwynedd Council has set up a Fairbourne Project Management Board to engage with the community and other stakeholders on the SMP, and to develop a plan for the move.

The EA (or NRW or SEPA) manage coastal flooding and keep a strategic overview over all forms of flood and erosion risk management, inland and at the coast, to ensure it is sustainable. Funding for coastal protection schemes is through 'partnership funding', where the Government pays a share (or sometimes all) of the total cost, and any shortfall is sourced elsewhere, usually from local authority funds or private sector investment. However, some local authorities suggest that it is challenging to fund coastal adaptation schemes via this funding source and it may result in just replacing defences following extreme events rather than the implementation of adaptation plans and strategies. A 2016 House of Commons Library briefing paper provides a detailed overview of Flood risk management and funding.

Adaptation for Coastal Communities and Cities
The UK CCRA further identifies risks from sea level rise to the viability of coastal communities (Box 4) as a research priority.[5] In major coastal cities, the number of people and property value at risk is extremely high, and relocation may not be an option.[47] Major coastal defence upgrades, informed by the SMPs, are being developed in Hull and Portsmouth.[72,73] However, adaptation responses will have to cope with long-term uncertainty and high-impact sea level rise scenarios.[74] The TE2100 'Adaptive Pathways' approach (Box 1) is widely considered as best practice in adaptive coastal planning, but is yet to be implemented in other UK coastal cities.

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